SIMULATION OF OCCUPANT KINEMATICS IN VEHICLE ROLLOVER - DUMMY MODEL VERSUS HUMAN MODEL

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ABSTRACT

Two different rollover crash scenarios were simulated with the software Madymo. The vehicle kinematics in the numerical simulation were prescribed by the use of sensor signals of real crash tests. The Madymo 50% Hybrid III dummy model as well as the Madymo human model was applied to these simulations and the model kinematics were analysed and compared.

Differences in the kinematics of human and dummy occupant models in rollover crash simulation will be presented and discussed with respect to car safety issues. Questions concerning the application and validation of human models in vehicle rollover will be considered and required investigations to improve occupant model performance in rollover simulations will also be addressed.

INTRODUCTION

In the past years the main topic in automotive safety were frontal, lateral and rear end impacts. As the injury risk in rollover crashes is high and an upward tendency of the incidence rate of rollover accidents may be expected due to increasing sales figures of Minivans and SUVs, occupant safety in rollover accidents becomes an area of great interest. In spite of this fact little is known about the kinematics of occupants in such situations. But the information about the occupant kinematics is very important to improve existing restraint systems (e.g. airbags, belt system) or to develop new safety systems for rollover accidents.

Compared to other car accident scenarios a rollover crash is characterised by a complex vehicle motion, a long duration and low linear accelerations. Because of those unique characteristics it is questionable whether crash tests with dummies which were developed for frontal, side or rear impact are useful measurement tools to understand the kinematics of occupants in rollover crash scenarios. So far no dummy for rollover crash tests is available and realistic rollover crash tests with volunteers are forbidden because of the high injury risk. So today the use of available standard dummies for frontal, side or rear impacts in rollover crash tests is the only way how to investigate occupant kinematics in rollover crash scenarios despite the above mentioned uncertainties.

Beside the real world crash tests there are virtual crash tests, i. e. numerical simulations of crash tests. The virtual tests are used especially in the development phase of new cars for a quick and cost saving investigation of different crash configurations and design variants. In those virtual tests numerical models of the car and the dummies are used to calculate the kinematics and dynamics of the crash. The numerical models of dummies are built and validated on the basis of real dummies, they are a kind of numerical copy of the real dummy. Because of that a simulation with those dummy models will not bring new insight into occupant kinematics.

In the last years the development of human models was intense (See Figure 1). Human models are built upon cadaver data, they are a kind of numerical copy of a human body. It is expected that the simulation with human models results in human-like kinematics and bypass the problem of the dummies in rollover crash scenarios. But today there is only little experience with the application of human models especially in complex crash scenarios.

Therefore the main objective within the overall goal of getting more knowledge about occupant kinematics in rollover accidents was to apply a human model in a virtual rollover crash test and to investigate the human model kinematics especially in comparison to the dummy kinematics. The kinematics of the human model as well as the dummy model is going to be discussed in view of their biofidelity. Future investigations needed to improve the performance of occupant models for rollover simulations are going to be addressed.

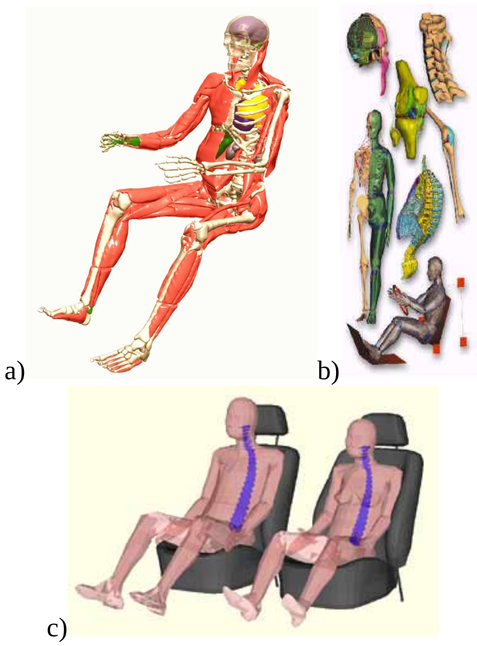

Figure 1. a) HUMOS-Model [1] b) ESI H-Model [2] c) Madymo Human Models [3].

METHOD

Vehicle Kinematics

Standard rollover crash tests of different type have been performed with a 50% Hybrid III dummy: a vehicle sliding sideways into a gravel pit, a vehicle driving down a bank, a vehicle driving up a ramp and a vehicle sliding laterally against a curb. The vehicle was a current popular passenger car. In this paper the first results of the crash test configuration "sliding laterally against a curb" and "sliding sideways into a gravel pit" are presented.

During the rollover crash test the linear accelerations (x-y-z-direction) and the rotational velocities (roll, pitch, yaw) of the vehicle were recorded (See Figure 2).

The recorded sensor signals were filtered and transformed from the local (car) coordinate-system into the inertial coordinate-system.

A lot of attention had to be paid on the transformation from local to global coordinate data, because it is not possible to transform local linear accelerations to global accelerations in the same way as transforming displacement data because of the gravity. So there was a need for some extra calculations to consider the gravity in the transformation process.

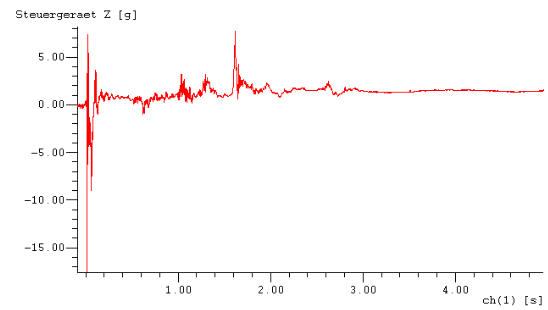

Figure 2. Measured linear acceleration in z-direction at the car COG (curb).

The result of the sensor signal processing was the vehicle kinematics in the inertial coordinate system. These kinematics from the rollover crash test were used to prescribe the motion of the vehicle in the numerical simulation.

Occupant Compartment

The occupant compartment model comprised car bottom, seats, belts, doors, roof, windows, steering wheel, knee bolster, and the instruments panel (See Figure 3).

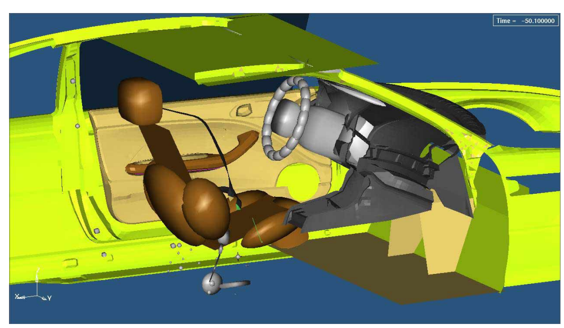

Figure 3. Occupant compartment model.

Doors, instruments panel and belts were modeled using finite element meshes. The steering wheel and knee bolster were built out of ellipsoids and for the roof and windows planes were used. Planes were also used for the seat base and the backrest whereas the side cushion of the seat was made up of ellipsoids.

Contact Definitions

In case the occupant comes into contact with the environment (occupant compartment) the forces between the environment and the occupant model have to be calculated. For that reason contact pairs have been defined before starting the simulation. For these predefined contacts force-deformation characteristics of the interior were acquired by component tests and used in the simulation model.

Validation of Occupant Compartment Model

Simulations with MADYMO 50% Hybrid III model were performed and the results were compared to the crash test results to validate the model set-up including seat cushions, FE belt, compartment geometry and vehicle motion. The comparison was done by a qualitative analysis of the car and occupant movement seen in the film of the crash test and in the visualisation of the simulation. Moreover, the time of contact between head and side window and the acceleration of the driver head in the crash test was compared to the simulation results.

Human model

Two different types of human models exist: multi body models and finite element models. With a multi body model one can calculate the kinematics and dynamics of linked bodies but no structural analysis (e. g. bone stress) can be done. In contrast to the multi body model the finite element model is useful for structural analysis on tissue level but needs a lot of computational time. The main interest of this investigation was the kinematics of the occupant model, therefore a multi body model was chosen for this study.

The MADYMO human occupant model, which is a multi body model developed by TNO, was used to investigate the occupant kinematics. It is made up of chains of rigid bodies connected by kinematic joints. Inertial properties, range of joint motion and joint characteristics are based on published biomechanical data. The outer geometry of the human occupant model is represented by facets to ensure reliable results for the contact of the skin with the interior including belt and airbags. The MADYMO human occupant model is a multi-directional occupant model with a flexible spine and a flexible torso. It is not designed for a specific impact direction and therefore it is suitable for complex vehicle accident scenarios like rollovers. The model is commercially available and has been validated against PMHS and volunteers for different impact situations [4].

Positioning

The human occupant model had to be placed in the correct position to get useful results from the simulations. So the joint angles were adjusted to meet the sitting position of a driver and the model was placed in the seat in such a way that an equilibrium between body weight and seat cushion forces occured, i. e. the occupant model was in rest.

For this purpose a pre-simulation prior to the rollover simulation had to be performed. In this pre-simulation the human model was put just above the surface of the seat and the simulation was started. The model dropped into the seat cushion and because of the damping of the seat cushion oscillated in a position with equilibrium of forces.

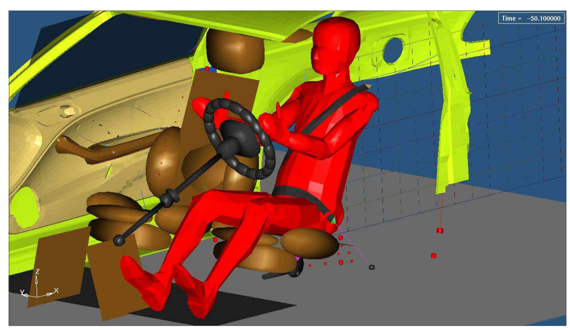

Figure 4. Human model in driving position.

The result of this first pre-simulation was the correct sitting position of the human occupant model. Starting from the result of the first pre-simulation the FE-belts had to be put on. Here another pre-simulation prior to the rollover simulation was needed. The FE mesh is placed very near to the outer geometry of the occupant model. Then a simulation was started where the end points of the belt moved backwards and so the belt was wrapped around the facets of the model. In the simulation output the point in time with the most realistic belt position was chosen and the FE coordinates at this time were taken as starting data for the correct belt position. After the two pre-simulations the model set-up was ready for the rollover simulations (See Figure 4).

Rollover Simulations

The occupant kinematics in two different rollover scenarios were simulated: sliding laterally against a curb and sliding sideways into a gravel pit. Both scenarios were simulated with the use of a dummy occupant model as well as with the use of a human occupant model.

The initial velocity of the car before sliding against the curb and before sliding into a gravel pit was 32,1 kph. The duration of the simulations was three seconds. For the simulations with the dummy model the integrator RUKA4 with a step size of 0.0001 was used wereas for the simulations with the human model the Euler integration with a step size of 0.00001 was necessary.

Evaluation

The occupant kinematics up to the first head to side window contact and the rebound short after the first head contact was analysed. The analysis was done qualitatively by looking at the overall kinematics of the occupant models in the simulations and quantitative by evaluating the time of the head to side window contact.

RESULTS

Validation

Before starting the rollover simulations the validity of the compartment model especially the seat and belt had to be checked. This was done by a comparison between the dummy model kinematics of the "sliding against a curb" and the dummy kinematics of the hardware crash test of the same rollover type. Figure 5 shows the acceleration of the dummy driver head in the test and simulation, respectively. The head contact in the test occured at 125 ms whereas the dummy head in the simulation hit the window at 135 ms (See Table 1). There is a difference of 10 ms which is acceptable for a rollover simulation. A qualitative analysis of the occupant kinematics showed only little deviations between dummy and dummy model movement. This proved that the occupant compartment including the seat and the belt was modelled in a reasonable way.

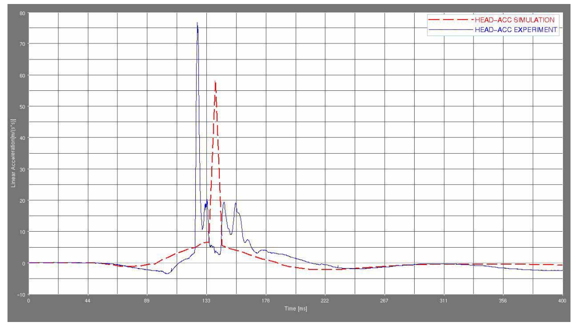

Figure 5. Head acceleration of the experiment (blue line) and of the simulation (red dotted line).

Table 1.
Comparison of experiment and simulation: time of head to side window contact

	Time of head to side window contact
Experiment	125 ms
Simulation	135 ms

Sliding against a curb

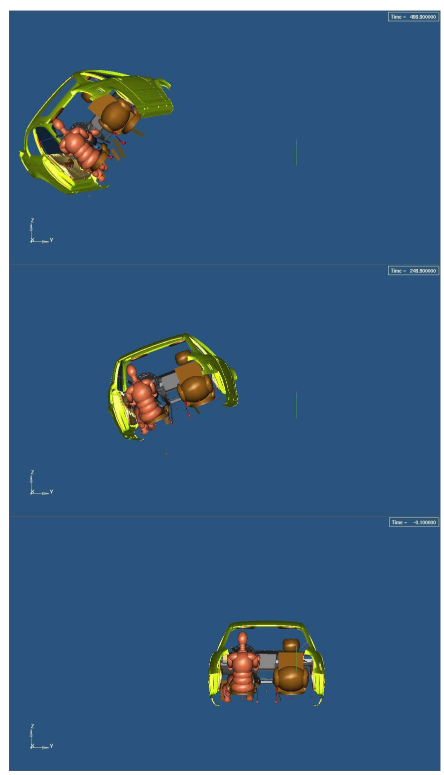

Figure 6. Vehicle movement "sliding against a curb" (sequence from bottom to top).

Figure 6 shows the vehicle kinematics of the first phase of the rollover simulation "sliding against a curb".

There are obvious differences in the kinematics of the human model and the dummy model as shown in the figures 7 to 9: the human model slides sideways to the door, the shoulder is contacting the door and the head is oriented parallel to the window until the head contacts the side window. The spine is only slightly bent. In contrast to the human model kinematics the dummy is sligthly tilted towards the door and the head is strongly tilted towards the side window. This results in a strongly bent cervical spine.

Despite of these differences in the kinematics the head of the human model contacts the side window only 9 ms prior to the head of the dummy model (See Table 2).

Table 2.

Time of head to side window contact for the simulation of "sliding against a curb"

	Time of head to side window contact
Human model	126 ms
Dummy model	135 ms

The reason for the tilting of the dummy model is its stiff "soft tissues" and its stiff torso. When the dummy is accelerated sideways the hip is immediately constrained by the lap belt because there is very little compliance of the body parts of the dummy. So the translational motion of the dummy model is limited and a torque around the hip is induced. The induced rotation around the hip is constrained by the lap belt too so the rotation movement is shifted towards the lumbar and thoracic region of the spine. This part of the dummy is less flexible than in the human model (and in real humans), there is no human like spine, i. e. no vertebras are modelled, and so there is only little flexibility in this region. This stiffness of the dummy torso and shoulder in combination with the flexible cervical spine results in a whip-effect of the head, i. e. the head is accelerated with respect to the upper body.

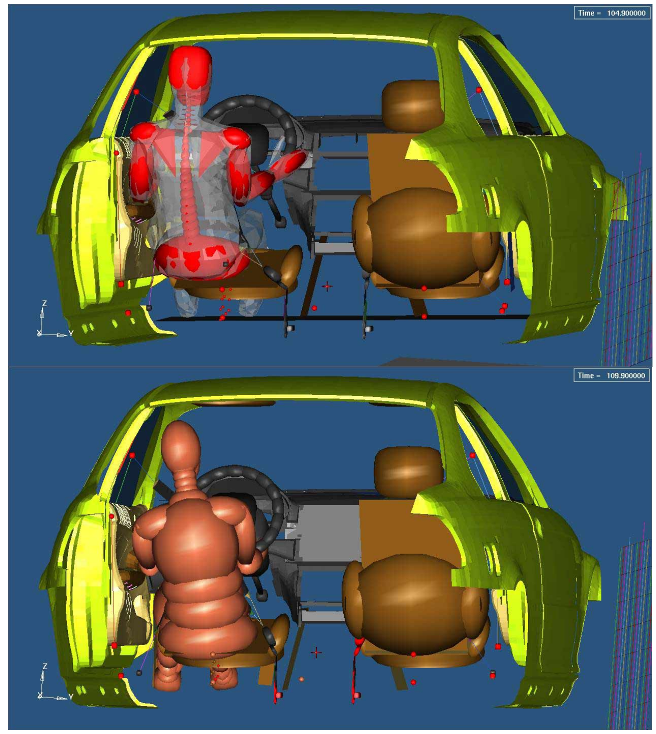

Figure 7. Occupant model position 30ms before head to side window contact (human model on top).

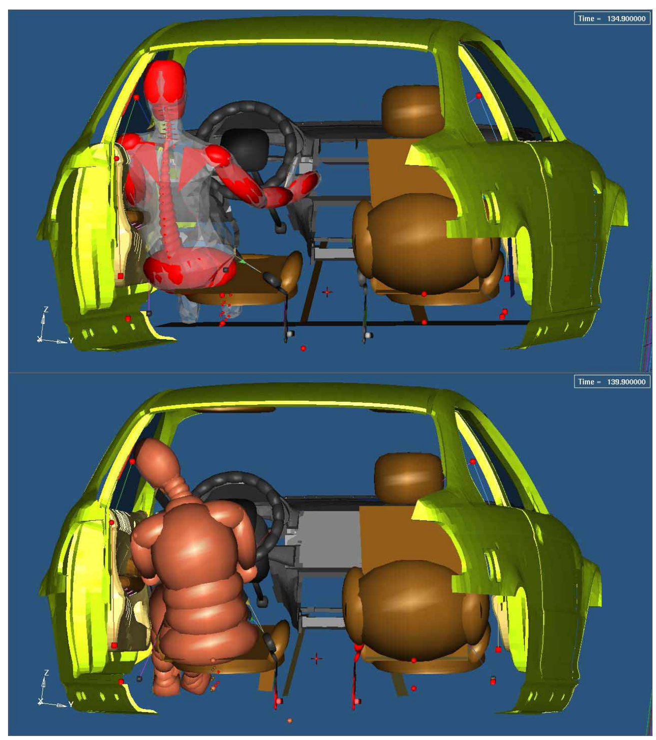

Figure 8. Occupant model position at head to side window contact (human model on top).

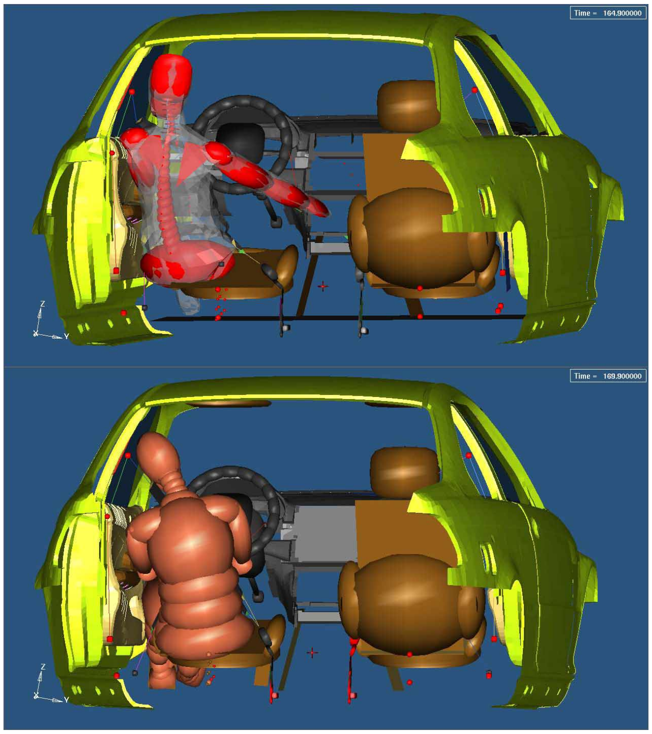

Figure 9. Occupant model position 30ms after head to side window contact (human model on top).

The difference between the dummy and human model kinematics caused by different body flexibility and pliability are well documented by the figures 7 to 9. This differences have an influence on the injury mechanics and therefore are important when looking for optimized restraint systems and safety design.

Sliding into a gravel pit

Figure 10 shows the vehicle kinematics of the first phase of the rollover simulation "sliding into a gravel pit". The vehicle kinematics of this rollover type shows in principle the same tilting movement as of "sliding against a curb". But this particular vehicle kinematics has a longer lateral deceleration phase when the vehicle is sliding in the gravel pit, the tilt starts later than in the "sliding against a curb". Figures 11 to 13 show in principle the same differences between the kinematics of the dummy model and the human model. But the head of the dummy model hits the side window 13 ms earlier than the human model (See table 3.).

Table 3.
Time of head to side window contact for the simulation of "sliding into a gravel pit"

	Time of head to side window contact
Human model	313 ms
Dummy model	300 ms

This finding is in contrast to the findings in the "sliding against a curb" rollover where the human model hit the window earlier than the dummy model. This shows that the differences between the dummy and human model kinematics can not be transfered from one accident scenario to another. The movement of a multi body system is a very complex process and depends strongly on the used model.

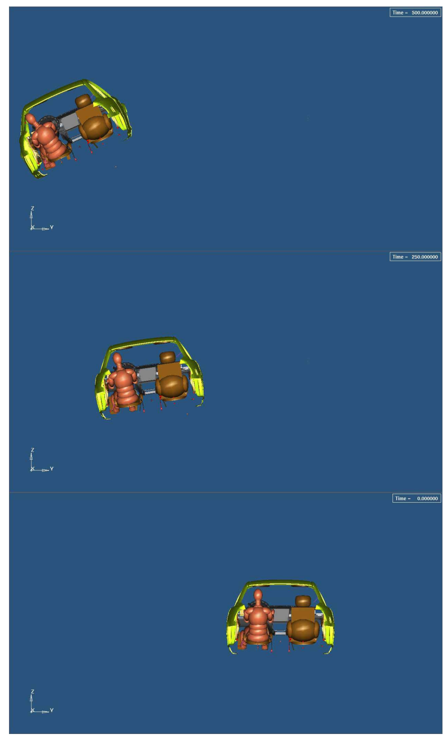

Figure 10. Vehicle movement of "sliding into a gravel pit" (sequence from bottom to top).

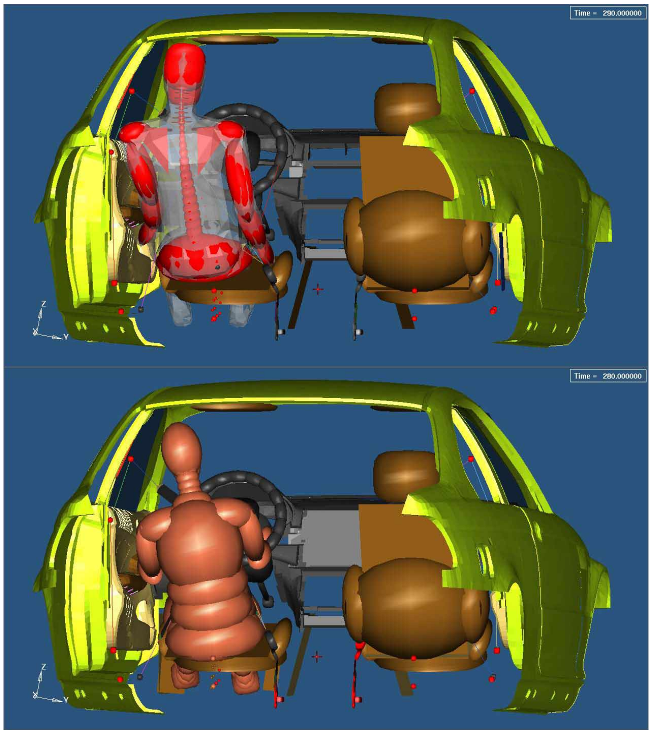

Figure 11. Occupant model position 30ms before head to side window contact (human model on top).

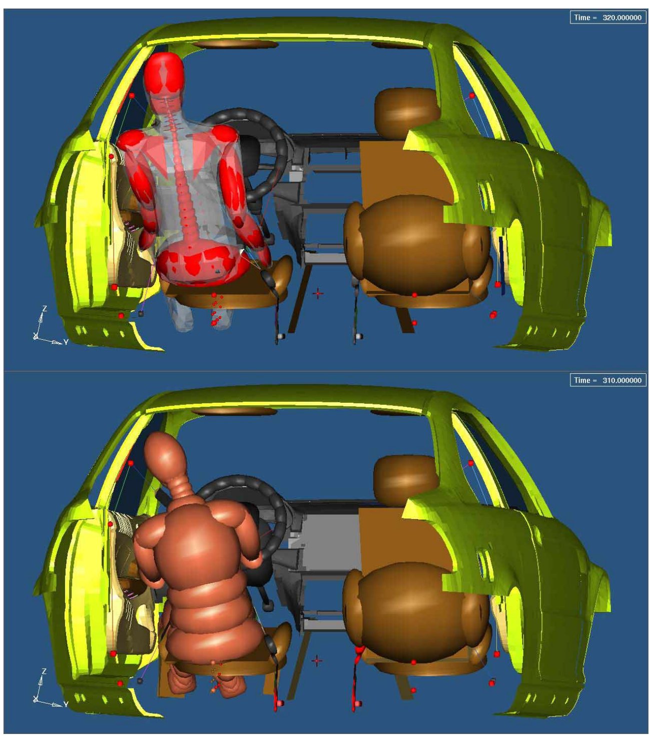

Figure 12. Occupant model position at head to side window contact (human model on top).

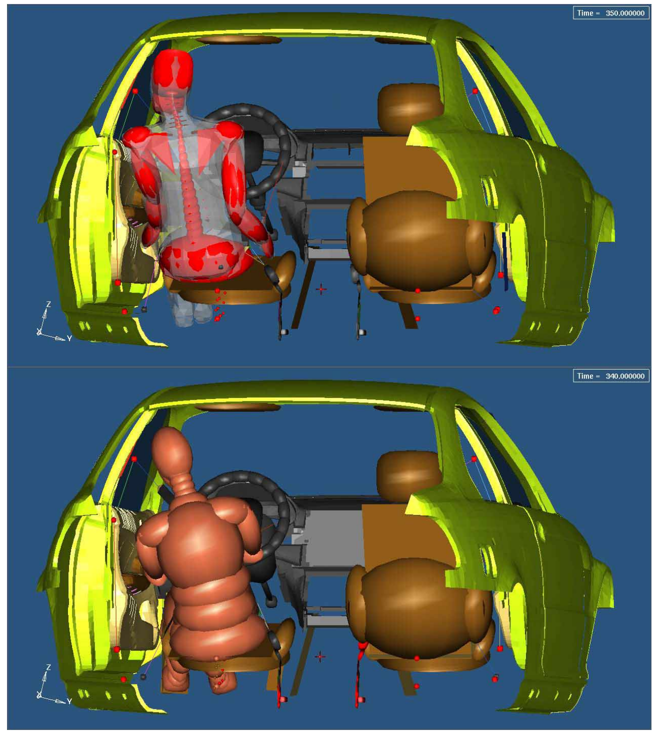

Figure 13. Occupant model position 30ms after head to side window contact (human model on top).

CONCLUSIONS

As a result of the kinematic differences between dummy and human occupant model the question about the consequences of these findings arises. There are two differences that have implications on the injury risk and therefore on the design of the restraint systems. The contact of the body with the door which is only seen with the human model and the unequal head movement of the two models. Looking at the human model kinematics a restraint system protecting the occupant from injuries caused by crashing into the door is recommended whereas the results of the dummy simulation indicate that there is no need for such a saftety system. The risk assessment of severe head injuries may be different depending on the occupant model used because the point of impact and the head position at impact is different and so the injury mechanism varies. Moreover the risk of getting the head out of the window may be influenced by the occupant model type as well. But at present further investigations are required for reliable conclusions in this respect.

In general numerical simulation can be a useful tool to determine the occupant kinematics needed for the design of safety devices. But the choice of the numerical representation of occupants is critical as our simulations demonstrate. To arrive at correct conclusions the results have to be interpreted carefully.

Crash test dummies (both the real ones and the numerical models) are rather mechanical devices than human bodies, their lack of biofidelity in certain situations is evident. Human models promise to be more human like than dummies, but the current human models are not perfect, either. Taking the pre crash phase into account or looking at crash scenarios with long duration it is not sufficient to represent the occupant as a dead body - the human models need refinements to get results directly comparable to real world situations.

These indispensable refinements of human models are related to the activity, motion control and behavior of living human beeings. So the modelling of this features is strongly dependent on the knowledge about these issues. Unfortunately there is no generally accepted and valid theory about human motion control enabling the computation of realistic muscle forces. Moreover the human behavior is task specific and stamped by the individual character. So there is a great need for more investigations into active human movements.

Because of ethical reasons it is impossible to validate occupant simulation results with experiments whenever severe impacts on the body are involved. The validity of a human like occupant model in severe impact situations can only be assessed by comparing injuries of accident victims with calculated model injuries of well documented real world accidents and their associated simulation.

To date occupant models are imperfect and so great care must be taken when choosing a numerical occupant model. The desired output as well as the given situation (front/side impact, duration, etc.) must be considered.

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